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**Nitric acid uptake to
mineral dust aerosol
particles**

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Effect of humidity on nitric acid uptake to mineral dust aerosol particles

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Abstract

This study presents the first laboratory observation of HNO_3 uptake by airborne mineral dust particles. The model aerosols were generated by dry dispersion of Arizona Test Dust (ATD), SiO_2 , and by nebulizing a saturated solution of calcium carbonate. The uptake of ^{13}N -labelled gaseous nitric acid was observed in a flow reactor on the 0.2–2 s reaction time scale at room temperature and atmospheric pressure. The amount of reacted nitric acid was found to be a linear function of aerosol surface area. SiO_2 particles did not show any significant uptake, while the CaCO_3 aerosol was found to be more reactive than the ATD. Due to the smaller uncertainty associated with the reactive surface area in the case of suspended particles as compared to bulk powder samples, we believe that we provide an improved estimate of the uptake kinetics of HNO_3 to mineral dust. The uptake coefficient averaged over the first 2 s of reaction time at a concentration of 10^{12} molecules cm^{-3} was found to increase with increasing relative humidity, from 0.022 ± 0.007 at 12% RH to 0.113 ± 0.017 at 73% RH , scaling along a water adsorption isotherm. The processing of the dust at 85% RH leads to a water soluble coating on the particles and enhances their hygroscopicity.

1. Introduction

Heterogeneous interactions between atmospheric trace gases and aerosols are important in several issues of atmospheric chemistry. The processing of atmospheric particles might affect the chemical and physical properties of the aerosol; on the other hand, it may also impact the global budget of important trace gas compounds. Among the many potential reactions occurring, the reaction of mineral dust aerosol with HNO_3 might be very important as it affects the ozone budget of the upper troposphere, because there the photolysis of HNO_3 is a significant source of NO and NO_2 , to which ozone sensitively responds (Bauer et al., 2004; Bian and Zender, 2003; Dentener et al., 1996).

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The heterogeneous reactions of mineral dust particles are also of significant interest because they could change the particle surface properties, which can therefore affect the properties of dust as cloud condensation or ice nuclei. The importance of this issue on a global scale has been demonstrated by several modelling studies (Kärcher and Lohmann, 2003; Lohmann et al., 2004). Laskin et al. (2005) reported field evidence of complete, irreversible processing of particles containing solid calcium carbonate and quantitative formation of liquid calcium nitrate particles, apparently as a result of the heterogeneous reaction of calcium carbonate with gaseous nitric acid. Such conversion of insoluble material to soluble material strongly affects the radiative properties of these aerosol particles as well as their ability to act as cloud condensation nuclei. Recent ambient studies have shown the ability of Saharan dust aerosol particles to form ice crystals in cirrus clouds (DeMott et al., 2003; Sassen et al., 2003). Currently, the question to what degree processing of dust particles by trace gases affects heterogeneous ice nucleation is subject of laboratory and field investigations (Archuleta et al., 2005).

Mineral dust is a complex mixture of different minerals, and its reactivity with trace gases obviously depends on the composition. To understand the mechanism of the heterogeneous interaction with dust one could study the reactions with each of the components. However, the reactive behaviour of complex mixtures is not only a superposition of the behaviour of their individual components. In addition, in practice it would be a hard task to complete due to the complexity of the dust composition. Therefore, in the case of HNO_3 , many studies have concentrated on identifying the most reactive components, among which is CaCO_3 , and assessing their reactivity (Fenter et al., 1995; Goodman et al., 2001; Hanisch and Crowley, 2001; Krueger et al., 2004). In the present work, the heterogeneous reactivity of CaCO_3 and SiO_2 has been compared to the reactivity of the Arizona Test Dust (ATD) aerosol particles. These components are chosen since quartz is one of the major (by weight) constituent of the dust in general and in the ATD in particular; and calcite is suggested to be one of the most reactive constituents of the dust (Usher et al., 2003). While many other studies focussed on Ca

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rich authentic dusts, ATD used in the present study is among the Ca poorer, though not less abundant forms of dust.

In this study, a dry dispersion generation method was used to produce submicron mineral dust aerosol and to measure the kinetics of the heterogeneous reaction with gaseous nitric acid with the aerosol particles in gas suspension. To our knowledge it is the first time that such a method was used for the production of a surrogate for atmospheric mineral dust in combination with a kinetic flow-tube technique. This approach is an alternative to the published studies of heterogeneous interactions in a Knudsen cell or with single particle techniques.

This study concentrates on basic uptake data and its dependence on relative humidity as well as the consequences on the hygroscopic properties of the dust particles. Ongoing, more detailed kinetic experiments will be reported elsewhere.

2. Experimental

The experimental method used is similar to the ones reported previously (Ammann, 2001; Guimbaud et al., 2002). Nitric acid labelled with a short-lived radioactive isotope ^{13}N is mixed with the aerosol particles in a flow reactor. After a certain reaction time, gas phase and particulate phase products are separated and trapped in a parallel-plate denuder and in a filter, respectively. The concentration of each species is measured by counting the number of ^{13}N decays in each trap per unit time. In this way, the loss of nitric acid from the gas phase and its irreversible uptake by the aerosol particle surface are measured simultaneously. The scheme of the setup is given in Fig. 1. Apart from the kinetic experiments, ATD aerosol particles were also processed by gaseous HNO_3 in a larger reactor. Hygroscopic properties of dust particles were studied before and after HNO_3 exposure using a HTDMA system described below.

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2.1. Production of HNO₃

The production of ¹³N in the form of ¹³NO has been described in detail elsewhere (Ammann, 2001). In brief, the ¹³N isotope is produced via the reaction ¹⁶O(p, α)¹³N in a gas-target, which is set up as a flow cell, through which 20% O₂ in He pass at 1 l/min stp at 2.5 atm, and which is continuously irradiated by 15 MeV protons provided by the accelerator facilities at Paul Scherrer Institute. The primary ¹³N molecules and radicals are reduced to ¹³N labelled NO over a TiC catalyst immediately after the target cell. The resulting gas is continuously transported to the laboratory through a 580 m capillary. There, a small fraction of this flow (typically 25 ml/min) is mixed with nitrogen as carrier gas (1 lpm) in our experiments. Additional amounts of non-labelled NO can be added from a certified cylinder (10 ppm in N₂) to vary the total concentration of NO within a range of 1 ppb to 1 ppm. NO is oxidized to NO₂ by reaction with ozone in a flow reactor with a volume of 2 l. Ozone is generated by passing a mixture of synthetic air in nitrogen through a quartz tube irradiated by a mercury penray UV lamp (185 nm wavelength). HNO₃ is produced from the reaction of NO₂ with OH radicals; the flow containing NO₂ is humidified to 40% relative humidity and irradiated by a second 172 nm excimer UV lamp to produce OH radicals, which rapidly convert a large fraction of NO₂ to HNO₃ (see results section).

2.2. Aerosol particle generation

In this study, two types of aerosol generation methods were employed: dry dispersion from a powder and atomisation of an aqueous solution. The dispersion of Arizona Test Dust and detailed characterisation of the resulting aerosol is published elsewhere (Vlasenko et al., 2005). Here only a short description of the technique is given. In a first step, the sample powder is dispersed by a solid aerosol generator (Topas GmbH, Dresden, Germany). Therein, a special belt feeds the dust to an injector nozzle in order to provide a constant input. Shear forces created in the injector disperse and disaggregate the powder to form submicron particles. In a second step, the remaining coarse

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particles are removed by a cyclone and a virtual impactor. This method is used to produce submicron particles from Arizona Test Dust (Ellis Components, England) and silica (Aerosil 200, Degussa, Germany). Calcium carbonate aerosol was generated by nebulizing a saturated aqueous CaCO_3 solution (Model 3075, TSI, USA). The resulting droplets are dried by passing the flow through a diffusion dryer. Charged particles from both aerosol sources are removed by passing the flow through an electrical precipitator. Finally, the aerosol flow is conditioned to a certain relative humidity. The humidifier is a vertically mounted tube with a H_2O permeable Goretex membrane (150 mm length, 6 mm i.d.) immersed in demineralised water. The relative humidity was measured by capacitance detectors at room temperature. The aerosol number concentration, size distribution and total aerosol surface area are controlled by a Scanning Mobility Particle Sizer (SMPS, TSI, USA). The size spectra of the aerosols obtained are given in Fig. 2. One can see that the particle concentration was largest for silica aerosol and lowest for the calcium carbonate particles.

2.3. Flow reactor for kinetic experiments

Mineral dust aerosol and nitric acid flows are mixed to react in the flow tube reactor with cylindrical geometry. The reactor is a PFA Teflon tube of 8 mm inner diameter and 10 mm outer diameter. The PFA Teflon material has been chosen to minimise the losses and retention of HNO_3 on the surface (Neuman et al., 1999). Gaseous nitric acid is introduced via an injector along the axis of the flow reactor. The injector is a PFA tube (i.d. 4 mm), which could be moved along the axis of the reactor. The position of the injector determines the gas-aerosol contact or reaction time. When the injector is pushed all the way in to the maximum position inside the flow reactor then the reaction time is minimum (0.2 s) and vice versa (2 s). The end of the injector tube is supplied with a special plug so that the gas enters the flow reactor through small openings at the end of the injector, perpendicular to the flow of aerosol. This is used to facilitate rapid mixing of the flows, which is critical for exactly controlling the reaction time. The degree of mixing was checked by measurement of the aerosol particle concentration

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upstream and downstream of the injection point by extracting a small flow with a small capillary pushed in from the opposite end of the reactor. The particle concentration was decreased immediately after the mixing with the gas flow in accord with the dilution factor of the corresponding volumetric flows. The flow tube is operated under laminar flow conditions, and it is assumed that the laminar flow profile is established a few cm downstream of the injector. The outer flow tube is replaced after each 6 hours of operation to avoid wall losses of HNO_3 driven by the particles deposited on the inner wall. The system is kept at room temperature. The relative humidity of the flow is continuously measured downstream of the reactor.

2.4. Detection system

The flow leaving the flow reactor was directly entering the parallel-plate denuder system. The latter captures the gaseous species HNO_3 , HONO , NO_2 on different chemically selective coatings by lateral diffusion. Note that this denuder train also effectively scrubs HNO_3 reversibly adsorbed to the particles. The sub-micron aerosol particles have a small diffusivity and pass through the denuder without being collected. Gaseous nitric acid is taken up in the first denuder section coated with NaCl . HONO is collected in the next section coated with Na_2CO_3 , while NO_2 is absorbed in the third section by reaction with NDA (N-(1-naphtyl) ethylene diamine dihydrochloride) mixed with KOH . These coatings are freshly prepared after each 6 h of operation. Generation of HNO_3 by reaction of NO_2 with OH is accompanied by ozone production under UV radiation. High concentrations of O_3 are not desirable because ozone reacts with the NDA-coating and depletes the capacity of the coating to absorb NO_2 . To minimise this effect the parameters of the HNO_3 generation (UV radiation exposure and amount of synthetic air) are optimised in a way to keep the output concentration of O_3 at minimum (below 30 ppb).

After passing the denuder, the aerosol particles are captured by a glass fiber filter. To each trap (the coatings and filter) a separate CsI scintillator crystal with integrated PIN diode is attached (Carroll and Ramsey, USA) which detects the gamma quanta emitted

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after decay of the ^{13}N atoms. The detector signal is converted to the flux of the gaseous species into the trap using the inversion procedure reported elsewhere (Guimbaud et al., 2002; Kalberer et al., 1996; Rogak et al., 1991). This flux is proportional to the concentration of the species in the gas phase.

5 An additional NaCl-trap is used to monitor the concentration of gaseous HNO_3 in a small side flow before entering the reactor. The trap consists of a quartz-fiber filter, soaked with a saturated aqueous NaCl solution and dried. Also to this trap, a scintillator device as that described above is attached. This measurement provides a “reference” for the generation of gaseous nitric acid and reduces the uncertainty related to the
10 instability of the flux of ^{13}N arriving in the laboratory. The relative counting efficiency of each detector is determined by accumulating a certain amount of H^{13}NO_3 in the “reference” trap and exposing it to each of the other detectors attached to the denuder sections and the particle filters in a way that closely mimics the geometrical configuration at each trap. The concentration of non-labelled NO and NO_2 is monitored by a
15 chemiluminescence analyser (Ecophysics, Switzerland). Further details of the preparation of the coatings, trap and filter efficiencies, and the performance of the detection system are published elsewhere (Ammann, 2001; Guimbaud et al., 2002).

2.5. Mineral dust processing and measurement of hygroscopic properties

Apart from the kinetic experiments, ATD aerosol particles were also processed by
20 gaseous HNO_3 in a laminar flowtube reactor at room temperature and atmospheric pressure over longer time scales. The mean residence time of the aerosol in this reactor was 3 min at a flowrate of 0.3 lpm. Relative humidity in the reactor was monitored by a capacitance detector. To vary the relative humidity in the reactor chamber, the aerosol flow passes through the humidifier (identical to the one described above). The
25 flow of HNO_3 was maintained by passing a 0.2 lpm flow of nitrogen through a bubbler, which contained a nitric acid solution in H_2O (0.1 M) at 12°C . Half of this flow was directed to a molybdenum converter held at 400°C and then to a NO chemilumines-

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cence detector to monitor the concentration of nitric acid in the gas phase (Joseph and Spicer, 1978). The concentration of gaseous HNO_3 detected in this way was 3×10^{13} molecules cm^{-3} at 298 K. The other half of the HNO_3 flow is mixed with the ATD aerosol flow (0.2 lpm) prior to the reactor entrance. After the reaction chamber, the aerosol flow was drawn through a NaOH coated denuder tube to remove HNO_3 from the gas phase. The hygroscopic properties of the processed ATD aerosol was measured by a Hygroscopicity Tandem Differential Mobility Analyzer (HTDMA) system described elsewhere (Weingartner et al., 2002). Briefly, in this instrument, the aerosol is first dried to a low RH ($<5\%$) and fed into the first differential mobility analyzer (DMA) where a monodisperse particle size fraction is selected (diameter $D=D_0$). Then, the aerosol is exposed to higher RH during ~ 60 s, and the resulting new particle size distribution is determined with a second DMA combined with a condensation particle counter. This instrument is capable of measuring the hygroscopic growth factor (GF) defined as the relative particle diameter increase from dry to humidified state, D/D_0 . A prehumidifier ($RH=95\%$) is included or bypassed in order to measure hygroscopic growth factors during dehydration or hydration.

3. Results and discussion

3.1. Procedure of the kinetic experiments

The time profiles of the NO_2 , $\text{HNO}_3(\text{g})$, HNO_3 (g-reference) and $\text{HNO}_3(\text{aerosol})$ concentrations during an individual uptake experiment is illustrated in Fig. 3 and described in detail below.

The experiment starts with equilibrating the system by running all gas flows without the admission of ^{13}N -labelled nitrogen dioxide (0–12 min time interval). At this time the background signals of the gamma detectors are recorded.

Then at 12 min, a small flow of $^{13}\text{NO}_2$ is admitted to the main gas flow. The NDA coating of the denuder starts to absorb nitrogen dioxide from the gas phase, accompa-

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nied by an increasing number of decays observed in this trap (panel A, dashed line). This growing signal is inverted to the flux of ^{13}N labelled molecules into this trap, which is proportional to the concentration of the $^{13}\text{NO}_2$ in the gas phase (panel A, solid line). Because this flux is calculated based on the difference of two consecutive activity measurements only, the inverted data (solid line) show more apparent scatter than the raw activity signals (dashed line). Prior to the reactive absorption in the NDA-trap the nitrogen dioxide molecules travel along the NaCl and Na_2CO_3 traps. Due to reversible adsorption and some slow conversion to HNO_3 and HONO, some of the ^{13}N atoms are also being absorbed on these traps, which leads to a small increase of the corresponding detector signals (panel B, solid line). For the same reason, the signal at the “reference” trap detector is increased (panel B, dashed line). The efficiency of the NO_2 absorption in the NDA-trap is not entirely 100%, so that a small fraction of NO_2 may penetrate the denuder to the aerosol filter and manifests itself as a slight increase of the signal (panel C). Note that this penetrating fraction may be extremely low but may still allow a detectable signal.

At 33 min of the experiment, the production of HNO_3 is started by switching on the UV lamp for OH production to convert NO_2 into HNO_3 . As a result, the detector signal of the NDA-trap decreases by about a factor of three (panel A, solid line). It indicates that two thirds of the labelled NO_2 molecules were oxidized to HNO_3 . We use this conversion factor to calculate the overall concentration of nitric acid in the gas phase by applying the same factor for the conversion of non-labelled NO_2 , the concentration of which is measured by the chemiluminescence detector. The increase of the HNO_3 concentration is detected at the NaCl denuder (panel B, solid line) and in the reference trap (panel B, dashed line).

The mineral dust particles are introduced to the flow reactor at 75 min of the experiment. The gas phase nitric acid concentration drops (panel B, solid line) due to reaction with the aerosol surface, while the concentration of the particulate HNO_3 increases (panel C). As noted above, the signal associated with particulate HNO_3 is due to HNO_3 irreversibly taken up to the particles. HNO_3 desorbing from the particles faster

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than 0.1 s would be detected as gas phase HNO_3 in the first denuder. No increase of the signals in the other denuders has been observed during the presence of aerosol, so that not significant amounts of HNO_3 desorbing on the time scale of a second while travelling along the denuder train had been associated with the aerosol. A significant loss of HNO_3 from the particles on the filter on the time scale of minutes would have resulted in a lack of mass closure for HNO_3 .

Using the procedure given here, uptake to aerosol particles can be measured as a function of reaction time, HNO_3 concentration in the flow tube and relative humidity. The algorithm to derive the value of the uptake coefficient from the measurements shown in Fig. 3 is described below.

3.2. Calculation of the uptake coefficient

The uptake coefficient is usually defined as the ratio between the net flux of molecules from the gas phase to the aerosol particles, J_{net} , and the gas-kinetic collision flux of the molecules to the surface of the particles, J_{coll} ,

$$\gamma = \frac{J_{\text{net}}}{J_{\text{coll}}} \quad (1)$$

The observations from an individual experiment shown in the previous section allow determining the rate of change of gas-phase and particulate phase concentrations. In principle, the mechanism leading to the net transfer of HNO_3 to an irreversibly bound product in the particulate phase can be very complex. Nevertheless, to obtain first insights into the kinetics, the uptake coefficient can be estimated in a first order approach similar to that reported earlier (Guimbaud et al., 2002). Note that this approach assumes a constant (quasi-steady state) uptake to the aerosol during the residence time of the aerosol in the flow reactor. Because, as noted above, reversibly adsorbed HNO_3 is not detected in the aerosol phase, the uptake coefficient obtained this way is the probability that an HNO_3 molecule colliding with the dust surface is irreversibly reacting with a dust component. Therefore, initial loss from the gas phase could be

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stronger than the quasi-steady state uptake coefficient assumed in this approach. The rate equation for the depletion of radioactively labelled HNO_3 from the gas phase in the cylindrical flow tube is given by

$$-\frac{dC_g}{dt} = (k_w + k_p) C_g \quad (2)$$

5 where C_g is the average concentration of HNO_3 in gas phase. k_w is the constant which describes the pseudo first order loss of H^{13}NO_3 from the gas phase due to its adsorption to the walls of the reactor. k_p is the constant, which describes the heterogeneous reaction between gaseous nitric acid and aerosol particles. The presence of the wall-loss is rather specific for the radioactively labelled molecules used in this study and will be discussed in detail in the next section. Integration of the Eq. (2) with respect to time gives the concentration of H^{13}NO_3 molecules in the gas phase as a function of time:

$$C_g(t) = C_g^{t=0} \exp \{ - (k_w + k_p) t \} \quad (3)$$

where $C_g^{t=0}$ is the initial concentration at time zero. k_w can be obtained from the measurement of the concentration of $\text{H}^{13}\text{NO}_3(\text{g})$ as a function of time in absence of aerosol ($k_p=0$). The loss rate of $\text{H}^{13}\text{NO}_3(\text{g})$ in presence of the aerosol then allows determining k_p .

The kinetics of appearance of H^{13}NO_3 in the particulate phase is given by:

$$C_p(t) = C_g^{t=0} \frac{1 - e^{-(k_w+k_p)t}}{1 + \frac{k_w}{k_p}} \quad (4)$$

where $C_p(t)$ is the concentration of H^{13}NO_3 in the particulate phase.

20 In practice, we used Eq. (4) and not Eq. (3) to calculate the constant k_p , because the experimental measurement of C_p is more accurate than that of C_g . The heterogeneous constant k_p is related to the effective uptake coefficient γ_{eff} according to following

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equation:

$$k_p = \frac{\gamma_{\text{eff}} S_p \omega}{4} \quad (5)$$

where S_p is the aerosol surface to volume ratio, ω is the mean thermal velocity of HNO_3 given by $\omega = (8RT/(\pi M))^{1/2}$, R is the gas constant, T is the absolute temperature and M is the molar weight of HNO_3 .

The value of S_p was measured in the experiment by the SMPS and the values of k_p and ω could be calculated using the equations listed above.

The value of the effective uptake coefficient, calculated in this way, depends slightly on the aerosol particle size, because gas phase diffusion affects the rate of transfer to larger particles more strongly than that to smaller particles. The diffusion correction was made using Eqs. (6) and (7) (Pöschl et al., 2005).

$$\frac{1}{\gamma} = \frac{1}{\gamma_{\text{eff}}} - \frac{0.75 + 0.28Kn}{Kn(1 + Kn)} \quad (6)$$

$$Kn = \frac{6D}{\omega d_p} \quad (7)$$

where D is the diffusion coefficient of HNO_3 , d_p is aerosol particle diameter and Kn is the Knudsen number. Note that for the experiments reported in this study, the correction was always below 5% as discussed below.

3.3. Retention of H^{13}NO_3 on the flow reactor wall

The observations show that there is a steady state drop of the gas phase concentration of H^{13}NO_3 during passage through the flow reactor even without aerosol. As already pointed out by Guimbaud et al. (2002), this is not due to an irreversible chemical loss of HNO_3 on the wall, but rather due to retention driven by adsorption and desorption. When considering the non-labelled HNO_3 molecules, this effect leads to the well-known

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slow response time of this sticky gas measured at the reactor outlet when switching it on and off. At low concentrations, the observed response time is directly related to the average residence time of individual molecules in the flow tube. If this residence time is comparable to the half-life of the radioactive ^{13}N -tracer, 10 min, a drop in the H^{13}NO_3 concentration along the flow tube can be observed, while the concentration of the non-labelled HNO_3 concentration remains constant, if equilibrium with the wall is established.

The details of lateral diffusion, adsorption, desorption, and radioactive decay are lumped into the pseudo-first order decay constant k_w . Therefore, Eq. (3) with $k_p=0$, was used to fit the experimentally observed $\text{H}^{13}\text{NO}_3(\text{g})$ concentration drop in absence of aerosol as shown in Fig. 4 for two examples. Typical residence times of HNO_3 derived from these loss curves are about 4 min. k_w obtained from these fits significantly decreased with increasing HNO_3 concentration, possibly because saturation coverage of HNO_3 on the PFA Teflon surface was reached above 10^{12} molecules cm^{-3} . k_w was also observed to increase with increasing relative humidity. This might be related to higher surface coverage by H_2O molecules at higher relative humidity and the formation of surface-adsorbed nitric acid-water complexes.

Apart from these effects, k_w also varied to some degree from tube to tube. Therefore, each time some parameter of the experimental system was changed or a new PFA flow tube was installed, a new measurement of k_w was performed.

3.4. Effect of aerosol surface area and “diffusion resistance” on uptake

The dependence of the amount of H^{13}NO_3 taken up on the aerosol of the aerosol surface area was investigated at an HNO_3 concentration in the gas phase of 10^{12} cm^{-3} , RH of 33% and reaction time of 1.9 s. The aerosol surface area was varied by changing the dust generator output, which results in a change of the particle number concentration but not particle size.

Figure 5 shows the number of HNO_3 molecules reacted per cm^3 as a function of the

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particle surface area per cm^3 . The error bars represent the 1σ deviation of data about the mean. The amount of nitric acid reacted on the surface should be a linear function of the particle surface area, as long as $(k_w + k_p)t < 1$, so that $C_p(t) \approx C_g^{t=0} k_p t$, and for fixed reaction time t , $C_p \propto S_p$. This confirms that our experiment lies well within pseudo-first order kinetics and that the availability of HNO_3 is not limiting the uptake.

To estimate the limitation of uptake by the diffusion of HNO_3 in the gas phase we use the expressions (6) and (7). The HNO_3 diffusion coefficient D has been taken as $0.118 \text{ cm}^2 \text{ s}^{-1}$ (Durham and Stockburger, 1986), which had been measured at atmospheric pressure, 298 K and 5–95% relative humidity. The “diffusion limitation” effect is stronger for higher values of the uptake coefficient. Based on Eqs. (6) and (7), the maximum correction $\gamma/\gamma_{\text{eff}}$ is 1.5 at 1 micrometer particle diameter for $\gamma_{\text{eff}} = 0.1$. When integrated over the full aerosol spectrum of ATD, the correction is about 5% or less for smaller values of γ .

3.5. Uptake coefficient on Arizona Test Dust aerosol

The experimental data of the $\text{H}^{13}\text{NO}_3(\text{g})$ concentration drop and the corresponding gain of $\text{H}^{13}\text{NO}_3(\text{p})$ in the aerosol phase shown in Fig. 6 was fitted using Eqs. (4) and (5), with k_p as independent variable. The constant k_p was varied using the least square method to achieve the best agreement between the data points of the concentration in the aerosol phase and model curve, calculated by Eq. (4), because, as noted above, the changes in the aerosol phase could be detected with better accuracy than those in the gas phase. The result is given in Fig. 5 and Table 2. The fit and the data agree quite well. One should notice that within accuracy of the experiment the drop of the $\text{HNO}_3(\text{g})$ concentration due to uptake to the aerosol corresponds to the growth of the $\text{HNO}_3(\text{p})$ signal. Most of the discrepancy between data and model has been assigned to the instability of aerosol generation. For instance, the deviation of the data points from the fit at 1.9 s reaction time in the example shown in Fig. 6 is due to an increase of the aerosol surface area recorded by the SMPS system at that time and as a result a

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higher uptake to the aerosol phase and stronger depletion of the HNO_3 concentration in the gas phase.

The uptake coefficient is found to be a function of HNO_3 concentration in the gas phase (Table 2). At higher concentration of nitric acid in the flow tube the uptake coefficient drops by more than a factor of three. Previous work on this and similar heterogeneous reaction systems indicate that the HNO_3 +mineral dust reaction could be considered as a two stage process: adsorption of HNO_3 on the dust surface followed by a reaction of the adsorbed HNO_3 with a basic surface site (surface OH-group on aluminosilicate or similar minerals or bulk CaCO_3). Therefore, the decrease of the uptake coefficient, which is an average over the two seconds reaction time, could be either due to the depletion of the reaction sites or due to saturation of the adsorbed precursor (Ammann et al., 2003). The available data points at $\text{HNO}_3(\text{g})$ concentration 10^{12} cm^{-3} still fit the model (which assumes an average uptake coefficient over the time scale of the experiment) reasonably well, so that depletion of the reactants during the early periods of the reaction time is likely not the reason for the concentration dependence. While the amount of HNO_3 found on the particle surface after two seconds of about $2 \times 10^{14} \text{ molecules cm}^{-2}$ could be considered close to a monolayer surface coverage, the degree with which components contained in the bulk of the particles can react and thus extend the capacity of the particles to react is not known. Therefore, this apparent non-first order behavior of the rate of product appearance indicates that the simple approach adopted here is not sufficient to retrieve a reliable parameterization of the kinetics. A more extended kinetic data set associated with proper kinetic modeling is necessary to extract the parameters describing the elementary processes of the uptake process. This will be part of a follow-up study of this, while here we concentrate on the humidity dependence.

3.6. Uptake coefficient on SiO_2 and CaCO_3 aerosols

In an attempt to understand the mechanism of the heterogeneous reaction between HNO_3 and the ATD and for the purpose of comparison with other studies, we also

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made experiments of uptake of HNO_3 to silica and calcite aerosol particles.

Figure 7 shows the uptake of the gaseous nitric acid to silica and CaCO_3 aerosol particles. To simplify the discussion of this comparison, we show the raw data in the same way as discussed in Sect. 3.1 above. The experiment starts with recording the background detector signal, as shown in Fig. 3. After 20 min, the aerosol is introduced into the flowtube, adjusted to a reaction time of 1.9 s. One may see that the detector signal level does not change with the introduction of SiO_2 particles at a statistically significant level. This means that silica aerosol seems rather inert with respect to reaction with HNO_3 . Assuming the detection limit at 3σ of the background noise level of the signal of the γ -detector at the aerosol filter and taking into account the measured SiO_2 aerosol surface area of $10^{11} \text{ cm}^2 \cdot \text{cm}^{-3}$, an upper limit to the uptake coefficient of 5×10^{-4} is obtained. This result is in agreement with the Knudsen cell study of Underwood et al. (2001) who reported the uptake of HNO_3 to a SiO_2 surface “too low to be measured”. Goodman et al. (2001) studied the heterogeneous reaction of silica powder with gaseous nitric acid using transmission FT-IR spectroscopy and classified the SiO_2 as a non-reactive neutral oxide with respect to this reaction. The authors also concluded that the adsorption of nitric acid on silica surface is reversible at 296 K. This is also in agreement with the data of the present study because HNO_3 reversibly adsorbed to the SiO_2 particles in the flowtube is desorbed in the denuder and not detected in the aerosol phase. This reversible nature of HNO_3 adsorption on silica surfaces was also reported by Dubowski et al. (2004) who found no significant amounts of covalently bonded nitrate on glass and quartz surface after exposure to HNO_3 .

In contrast, CaCO_3 particles are more reactive with respect to nitric acid than ATD, as also shown in Fig. 7. The uptake to CaCO_3 is almost 4 times higher than to ATD. This is not surprising, since the reactivity of CaCO_3 with HNO_3 is well known, while ATD contains only little CaCO_3 but much more of the less reactive silica and aluminosilicates. This is in agreement with the studies of Krueger et al. (2003, 2004), which showed the formation of $\text{Ca}(\text{NO}_3)_2$ in single CaCO_3 and authentic dust particles as a reaction product at conditions close to the experimental conditions of this study (RH

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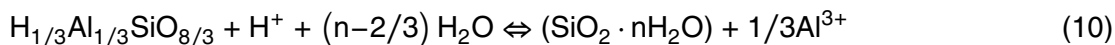
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38%, HNO_3 concentration 4.6×10^{11} molecules cm^{-3}).

To some extent the nature of the mineral surface under the humid conditions of the present study could be rationalized from the way how the major mineral constituents are expected to dissolve in near neutral or acidic aqueous solution (Desboeufs et al., 2003; Schott and Oelkers, 1995) :



This list of reactions is not complete and one should also consider the dissolution of minor components of the ATD: microcline, illite, etc. Most of these minerals dissolve similar to albite and some could additionally release Mg^{2+} cations. Exposure of ATD to HNO_3 under humid conditions certainly helps promoting these hydrolysis processes by providing protons. Even though these hydrolysis processes might not be complete on the surface, especially at relatively low humidity, partial solvation might be enough for providing a reactive site to HNO_3 .

3.7. Effect of humidity on uptake

The hydrolysis Reactions (8) to (11), which might promote the surface (and eventually also bulk) reactivity of dust towards HNO_3 , are directly suggesting that a significant humidity dependence should exist. The effect of variation in relative humidity on the uptake coefficient was investigated using a fixed HNO_3 concentration of 10^{12} molecules cm^{-3} and a fixed reaction time of 1.9 s. The data displayed in Fig. 8 indeed show that γ increases steadily from 0.022 ± 0.007 at 12% *RH* to 0.113 ± 0.017 at 73% *RH*.

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A possible explanation to this is the increasing amount of H₂O adsorbed on the surface of ATD particles, which may promote the hydrolysis processes. Some information on the amount of water associated with ATD aerosol can be obtained from the hygroscopic growth of ATD aerosol particles investigated in a previous study (Vlasenko et al., 2005). The main conclusion was that the ATD particles adsorb water under increasing *RH* conditions, to some degree related to the presence of water soluble material. However, the small size changes did not allow retrieving a well resolved water adsorption isotherm. For bulk oxide materials it has been shown that several monolayers of water can be formed on the surfaces of SiO₂, Al₂O₃ and CaCO₃ with increasing relative humidity (Al-Abadleh and Grassian, 2003; Goodman et al., 2001, 2000). Similar behavior was shown for water adsorption on a borosilicate glass surface (Dubowski et al., 2004; Sumner et al., 2004). These authors have adapted the BET equation (Adamson, 1982) to describe water adsorption on the surface of solids. We used the same approach to calculate the isotherm for the adsorption of water by

$$\Theta_{\text{H}_2\text{O}} = \frac{cRH}{(1 - RH)(1 - (1 - c)RH)} \quad (12)$$

One can see in Fig. 8 that this isotherm can be well fitted to the experimental data of the uptake coefficient of HNO₃ on ATD. This observation continues the row of “BET isotherm like” humidity dependent heterogeneous reactions on solid surfaces: HNO₃(g)+NaCl(s) (Davies and Cox, 1998), HNO₃(g)+CaCO₃(s) (Goodman et al., 2000), NO₂+1,2,10-anthracenetriol (s) (Arens et al., 2002) and NO₂+borosilicate glass (Finlayson-Pitts et al., 2003), in all of which hydrolysis of the substrate provides the reactive components. This contrasts other heterogeneous processes, such as oxidation reactions (Adams et al., 2005; Pöschl et al., 2001), in which water adsorption competes with the adsorbing gaseous reactant, so that humidity has an inhibiting or no effect on the overall process.

Furthermore, the increase of the uptake coefficient with humidity measured in this study is consistent with data from the ACE-Asia field campaign, where the mass accommodation coefficient of HNO₃ on ambient dust was found to depend on *RH*

(Maxwell-Meier et al., 2004).

3.8. Comparison to literature data

Several aspects should be considered, when comparing the uptake data of the present study to those currently available in the literature as listed in Table 3. Our data suggest a strong humidity dependence of the uptake coefficient, while the previously available kinetic studies were all performed under completely dry conditions. If we would extrapolate our data along the water adsorption isotherm to very low humidity (0.1% RH) in Fig. 8, we expect the uptake coefficient to get into the range of 10^{-3} for ATD, and a similar shift might be expected for the uptake on CaCO_3 , if we would assume a similar dependence on humidity. Hanisch et al. (2001) report an about a factor of 2 change in the uptake coefficient on CaCO_3 measured under dry conditions, when water remaining after evacuation was further removed by baking the dust powder.

A second aspect relates to the issue of surface area to normalize the uptake according to Eq. (2). The significant disagreement between the values reported by Goodman et al. (2000) and by Johnson et al. (2005) on the one hand and those reported by Fenter et al. (1995) and Hanisch et al. (2001) on the other are due to different ways of taking into account internal surface areas of the powders used. Goodman et al. (2000) measured the specific area of CaCO_3 powder with a BET method and applied the Keyser-Moore-Leu model (Keyser et al., 1991) to account for the contribution by the internal surface area, while Fenter and Hanisch referred to the geometric sample surface area to calculate the collisional flux in the molecular flow regime to the external powder surface. In our study with suspended aerosol particles, we estimate the reactive surface area from the measurement of the mobility diameter (measured by SMPS) and assuming that the particles are spherical, even though it has been shown (Vlasenko et al., 2005) that the ATD particles used in this study are not perfectly spherical and could be to some degree agglomerates, especially for particle sizes larger than 200 nm. Experimentally, the relation between the surface of aerosol agglomerates available for reaction and the surface measured by SMPS is only known for a perfectly sticking ($\gamma=1$)

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species, namely ^{211}Pb atoms. Rogak et al. (1991) experimentally proved that the mobility diameter measured by SMPS is equal to the “mass transfer” diameter not only for spherical particles but also for complex agglomerates, namely soot. Other existing theoretical approaches to account for the additional internal surface of aerosol agglomerates rely strongly on empirical parameters (Naumann, 2003; Xiong et al., 1992). In the absence of a more accurate way to evaluate the true dust surface area (available for reaction with HNO_3) we used the surface area measured by the SMPS system to calculate the uptake coefficient. Bearing in mind that only part of all the particles are slightly agglomerated (particles larger than 200 nm) we guess a not more than 20% systematic underestimation of the dust surface area given by the SMPS.

Therefore, the apparent agreement of the uptake coefficients observed under humid conditions of this study with those of Hanisch and Fenter for CaCO_3 and Hanisch and Seisel for ATD under very dry conditions might be accidental, And our data might be in closer agreement with the Goodman and Johnson data than it would seem at first glance.

3.9. Implications for the hygroscopic properties of ATD aerosol

One of the atmospherically relevant consequences of the heterogeneous interaction between $\text{HNO}_3(\text{g})$ and mineral dust is the associated change of hygroscopic properties of the dust particles. Figure 9 shows the hygroscopic growth of ATD particles before and after reaction with gaseous nitric acid and water vapor. When dust particles are exposed to HNO_3 (3×10^{13} molecules cm^{-3}) for 3 min at 30% relative humidity the hygroscopic properties do not change significantly (Fig. 9a). The exposure in this experiment corresponds to the integrated exposure of an atmospheric dust particle to 0.1–1 ppb of HNO_3 during a typical life-time of 1–10 days, even though we are aware that in view of the concentration dependence observed this might be an over-simplification. The ATD hygroscopicity is significantly changed after weathering the particles at the same concentration of HNO_3 and 85% *RH*. Figure 9b shows that after the exposure the par-

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ticle diameter is increased by 7% while increasing the humidity from 10% to 78%. This finding is consistent with the kinetic data that show a strong effect of humidity on the speed and extent of processing of the dust particles by HNO_3 (Fig. 8).

Even though the formation of a liquid phase is thermodynamically not favored (for the pure $\text{HNO}_3\text{-H}_2\text{O}$ system) under our conditions, we nevertheless assume that the concomitant exposure to nitric acid and high humidity of 85% over longer time scales promotes the significant dissolution of the particle surface material through Reactions (8) to (11) (Desboeufs et al., 2003; Schott and Oelkers, 1995). Desboeufs et al. (1999) studied the dissolution rates of different elements from Sahara dust at different pH and reported the increasing solubility sequence $\text{Si} < \text{Mg} < \text{Ca} < \text{K} < \text{Na}$. From these data we concluded that the uptake of HNO_3 from the gas phase to mineral dust particles at 85% *RH* increases the acidity of the adsorbed water layers and strongly promotes the dissolution of major minerals. The weathering of silica is believed to be small on a time scale of our experiment (3 min). In our experiments, after the processing the aerosol was dried, and possibly separate phases of Ca/Mg/Na nitrates are formed on the particles. Laskin et al. (2005) interpreted the increase the O,N atomic content of the Ca-rich mineral dust particles after $\text{HNO}_3(\text{g})$ exposure as formation of calcium nitrate. We use the assumption (that the reaction product is $\text{Ca}(\text{NO}_3)_2$) to calculate the amount of product built up after processing of ATD with gaseous nitric acid. Using the approach of Saathoff et al. (2003) and assuming spherical shape of particles and independent additive hygroscopic behaviour of the different components one may calculate the volume fraction of $\text{Ca}(\text{NO}_3)_2$ coating on the processed particles according to the following equation:

$$\epsilon = \frac{GF_{\text{proc}}^3 - GF_{\text{nonproc}}^3}{GF_{\text{Ca}(\text{NO}_3)_2}^3 - GF_{\text{nonproc}}^3} \quad (13)$$

where GF_{proc} and GF_{nonproc} are hygroscopic growth factors of the processed and non-processed ATD particles, respectively. $GF_{\text{Ca}(\text{NO}_3)_2}$ is a hygroscopic growth factor of pure calcium nitrate, which is quite similar to the other soluble nitrates in dust (sodium

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nitrate and magnesium nitrate).

Using the measured values of the hygroscopic growth factors (Fig. 9b) for the ATD and the literature value for the calcium nitrate hygroscopic growth (Tang and Fung, 1997) as a proxy for the behaviour of the soluble nitrates, we calculate a 8% volume fraction of $\text{Ca}(\text{NO}_3)_2$ in the processed particles. Expressed as an external coating, this corresponds to an about 1 nm thick layer. This rough estimate shows that several monolayers of hygroscopic reaction products could be formed on the surface of the ATD particles as a result of processing with gaseous nitric acid. Note that extrapolation of our processing experiment to atmospheric conditions is only valid under the assumption that the degree of processing is a function of the integrated exposure only and not a function of HNO_3 concentration during the exposure.

4. Atmospheric implications

The major atmospheric implication of this study is the experimentally determined humidity dependence of the heterogeneous uptake on the dust aerosol. It has been shown that increasing the relative humidity promotes the uptake of nitric acid. However, recent modeling studies (Bauer et al., 2004; Bian and Zender, 2003; Tang et al., 2004) consider the heterogeneous reactivity of the dust independent of relative humidity. While the order of magnitude of the uptake coefficient used by Bauer et al. (2004) based on the data of Hanisch and Crowley (2001) obtained under very dry conditions ($RH < 1\%$) is similar to what we report here, we strongly suggest that a humidity dependent uptake coefficient scaling along a water isotherm as shown in Fig. 8 could be used in modeling studies. Implementing this dependence into global dust models will certainly reduce their uncertainty.

Another atmospherically relevant outcome of the present study is the experimental evidence that extensive processing of mineral dust by $\text{HNO}_3(\text{g})$ and possibly other acidic gases results in significant hygroscopic growth. The enhanced water uptake by dust particles increases their interaction with solar radiation. To illustrate this effect we

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estimate an increase of the dust single scattering albedo (SSA). SSA is the commonly used measure of the relative contribution of absorbing aerosol to extinction and is a key variable in assessing the climatic effect of the aerosol (Seinfeld et al., 2004). Assuming that the processing does not change the refractive index ($n=1.52$, $k=0.00133$) of the dust shown on Fig. 9b and only increases the particle size we estimate 3% increase of the SSA for the aged dust at 550 nm wavelength of incident light. This calculation is very crude but indicates the potential of the dust aging process to affect the radiation balance of the planet.

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Table 1. Flow reactor parameters and measurement conditions.

Parameter	Value
Reaction time	0.2–2 s
Concentration H^{13}NO_3 (labelled)	$\sim 10^6 \text{ cm}^{-3}$
Concentration of HNO_3 (not labelled)	$10^{11}–10^{12} \text{ cm}^{-3}$
Pressure	$\sim 1 \text{ atm}$
Relative humidity	12–73%

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Table 2. Conditions of the uptake experiments and the results of the fits to the data.

parameter	HNO ₃ concentration in the gas phase in flow reactor, molecules cm ⁻³	
	(1±0.5)×10 ¹¹	(10±1)×10 ¹¹
<i>RH</i> , %	33±1	33±1
<i>S_p</i> ×10 ⁻⁵ , cm ² cm ⁻³	8.6±0.5	12.9±0.3
<i>k_w</i> , s ⁻¹	0.152±0.002	0.110±0.003
<i>k_p</i> , s ⁻¹	0.063±0.005	0.025±0.005
<i>γ_{eff}</i>	0.10±0.01	0.03±0.01
<i>γ</i>	0.105±0.01	0.03±0.01

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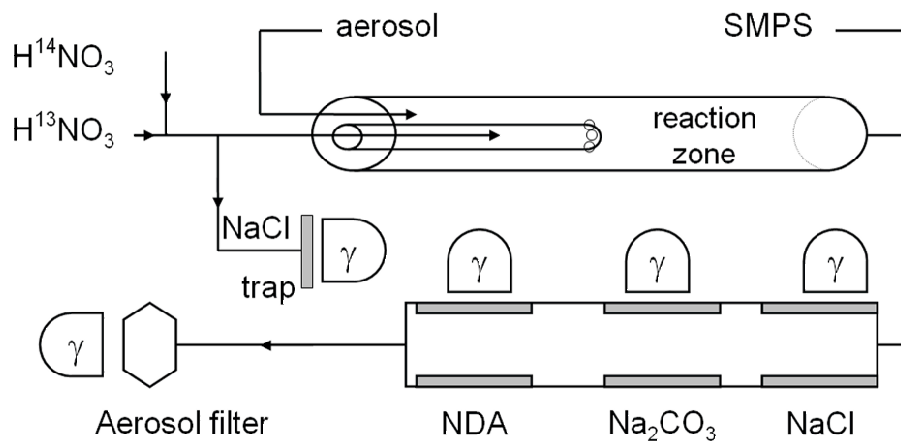
Table 3. Uptake coefficient measured for aerosol particles of different composition. KC, DRIFTS and FT are abbreviations of Knudsen Cell, Diffuse reflectance infrared spectroscopy and Flow Tube reactors, respectively. Only average values of uptake coefficients and orders of magnitude HNO_3 concentrations are given for conciseness. * Values are given for nonheated and heated sample respectively. ** Uptake measured at *RH* 33%.

Study	Reactor	Sample	HNO_3 Conc, cm^{-3}	Composition		
				SiO_2	CaCO_3	ATD
Fenter et al. (1995)	KC	powder	$10^{10}\text{--}10^{13}$		0.15	
Goodman et al. (2001)	DRIFTS	powder	$10^{14}\text{--}10^{15}$	10^{-9}		
Goodman et al. (2000)	KC	powder	10^{12}		2.5×10^{-4}	
Johnson et al. (2005)	KC	powder	10^{11}		2×10^{-3}	
Hanisch et al. (2001)	KC	powder	$10^{14}\text{--}10^{15}$		0.18, 0.1*	
			$10^{11}\text{--}10^{12}$			0.06
Seisel et al. (2004)	DRIFTS	powder	$10^{11}\text{--}10^{12}$			0.012
this work**	FT	aerosol	10^{12}	$<5 \times 10^{-4}$	0.11	0.03
			10^{11}			0.11

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**Fig. 1.** Schematic diagram of the flow reactor and detection system.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

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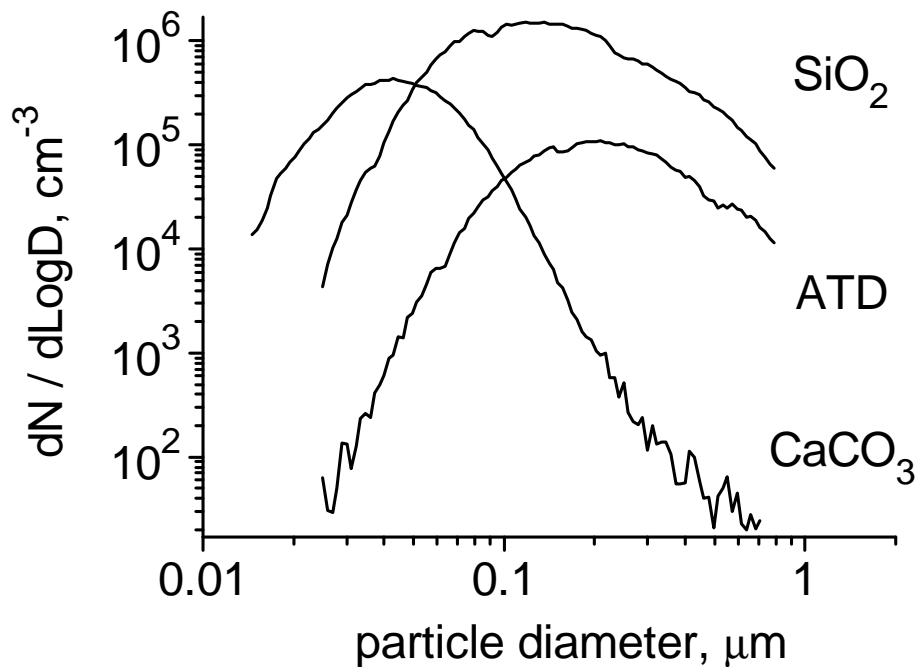


Fig. 2. Size distribution of aerosol particles used to study the heterogeneous reaction with gaseous nitric acid.

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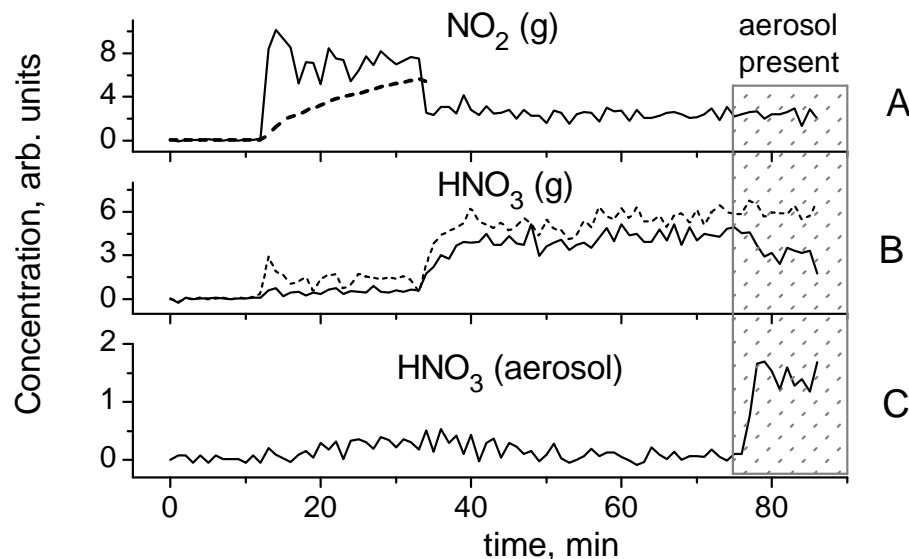


Fig. 3. Online record of an uptake experiment. Panel **(A)**: dashed line represents the signal of γ -detector at the NDA-trap and solid line corresponds to the concentration of nitric dioxide. Panel **(B)**: the dashed line represents the “reference” gas phase concentration of HNO_3 (concentration before entering the reactor) and the solid line corresponds to the concentration after the reactor. Panel **(C)**: the solid line represents the concentration of nitric acid on the aerosol surface. The grey bar (75–90 min) corresponds to the time when aerosol was present in the flow reactor. The HNO_3 gas phase concentration in the flow tube was 10^{11} cm^{-3} and RH 33%.

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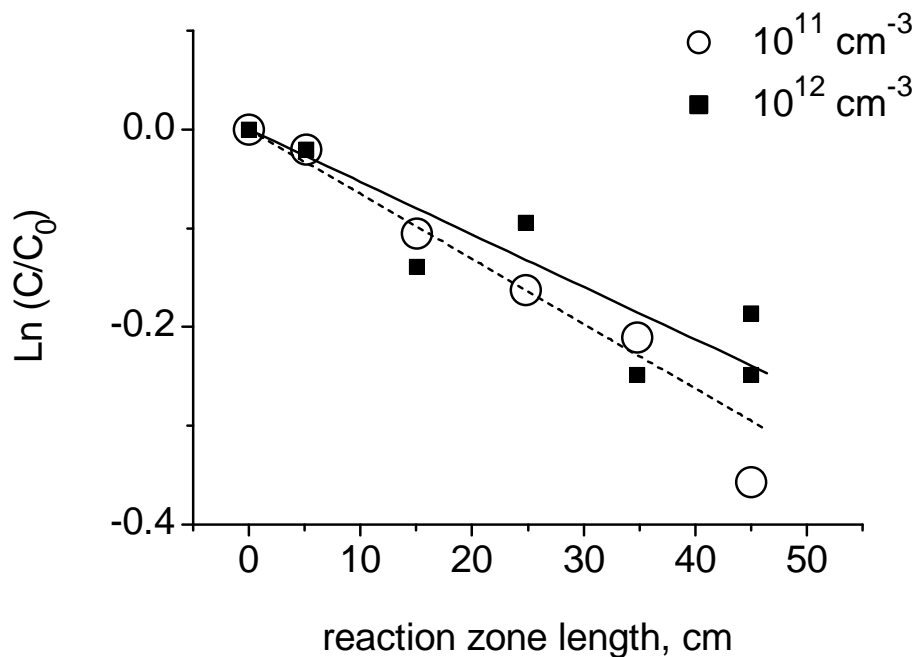


Fig. 4. Concentration of H^{13}NO_3 leaving the flow reactor in absence of aerosol at different injector positions, normalized by the initial concentration. Circles and squares represent the data points measured at 10^{11} cm^{-3} and 10^{12} cm^{-3} , respectively, of HNO_3 in flow tube and 33% *RH*. Lines are fits to the data according to the model explained in the text.

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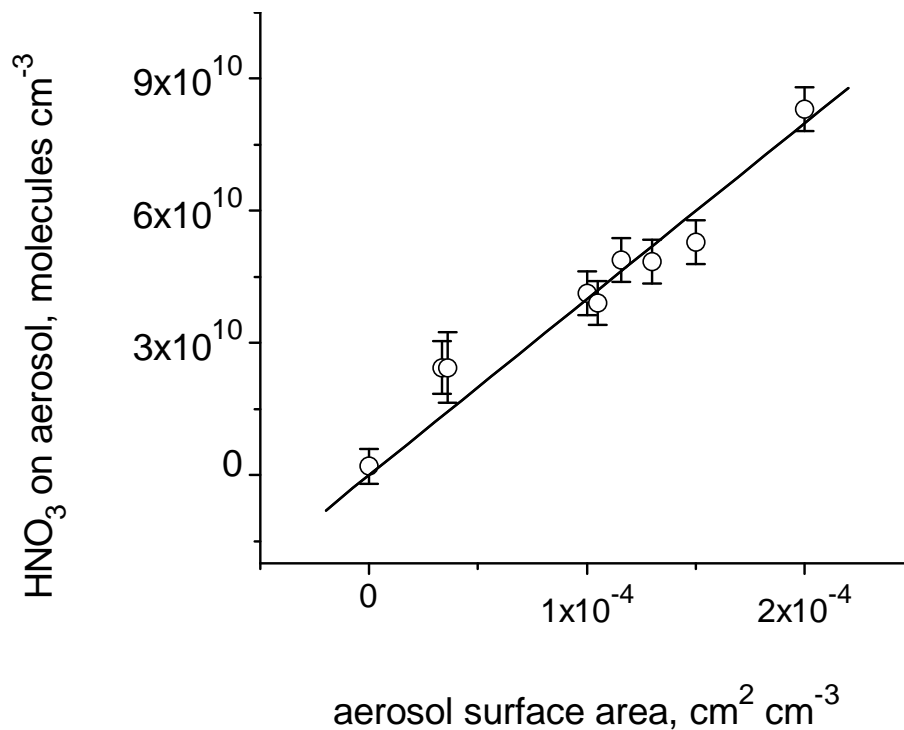


Fig. 5. HNO₃ reacted with ATD particles as a function of specific aerosol surface area. The nitric acid gas phase concentration in the flow tube was 10¹² cm⁻³ and *RH* 33%.

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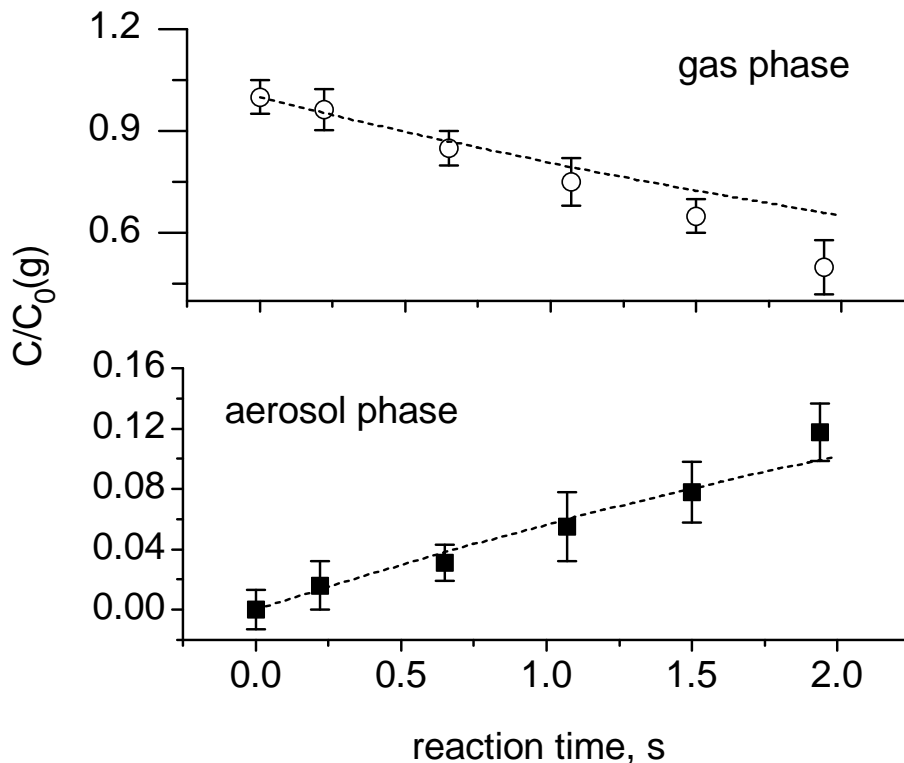


Fig. 6. Change of the HNO_3 concentration in the gas (open circles) and particulate (solid squares) phases as a function of reaction time. Experimental data are represented as the concentrations normalized by the concentration in the gas phase at reaction zero time. The dashed lines are the model fits. The HNO_3 gas phase concentration in the flow tube was 10^{11} cm^{-3} and RH 33%. The error bars represent the 1σ deviation of data about the mean.

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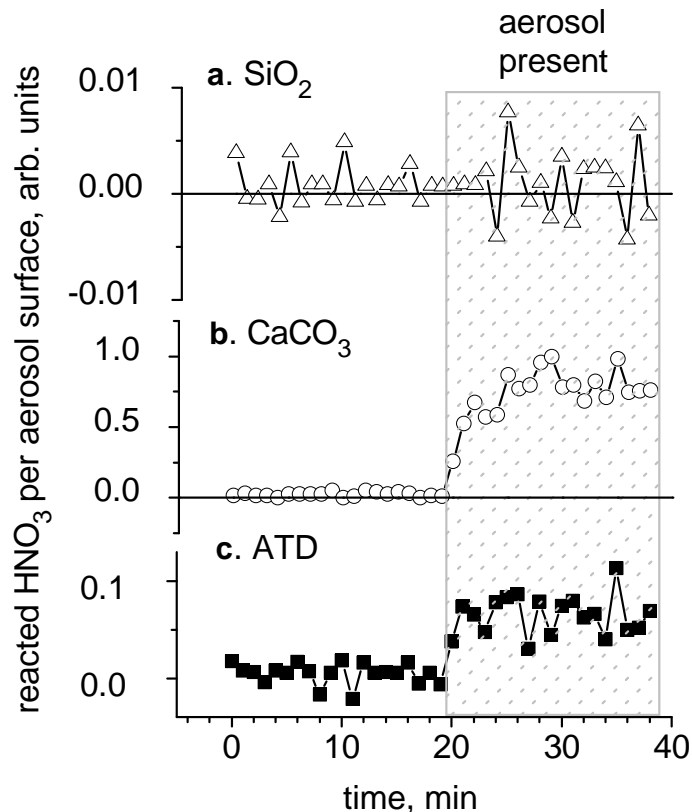


Fig. 7. Online record of uptake experiments between gaseous HNO_3 and aerosol particles of different materials. Panels (a), (b), (c) represent the reactions with the aerosol composed of silica, calcium carbonate and Arizona Test Dust, respectively. The time period 0–20 min corresponds to the background readings of the detector. The grey bar (20–40 min) corresponds to the time when aerosol was present in the flow reactor. The HNO_3 gas phase concentration in the flow tube was 10^{12} cm^{-3} and RH 33%.

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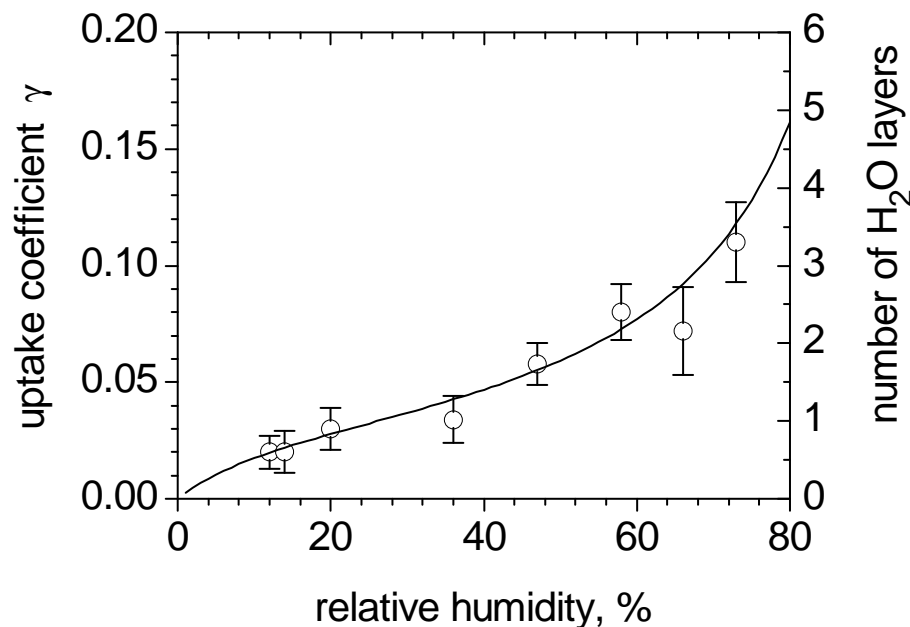


Fig. 8. Uptake coefficient of nitric acid to ATD mineral dust aerosol as a function of relative humidity. Open circles represent the experimental values of the uptake coefficient reaction time 1.9 s, the concentration of nitric acid in the flow tube was 10^{12} cm^{-3}). The solid line represents a BET isotherm (Eq. 8, $c=8$) for water adsorption, scaled to match the uptake data.

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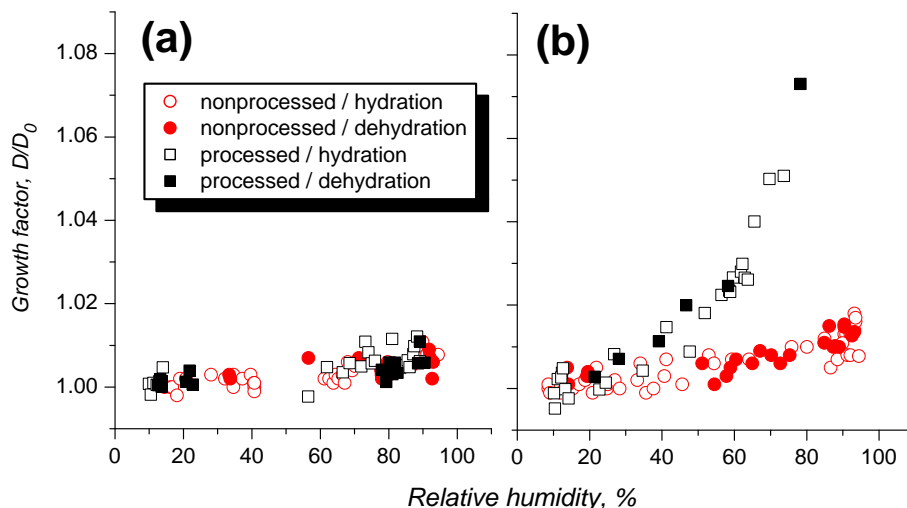


Fig. 9. Hygroscopic growth of ATD particles before (circles) and after (squares) reaction with gaseous nitric acid (3×10^{13} molecules cm^{-2}) and water vapour. **(a):** circles represent ATD particles with $D_0 = 100$ nm before reaction, squares represent particles of the same size after reaction with HNO_3 at 30% RH. **(b):** circles represent ATD particles before reaction, squares represent ATD particles after reaction with HNO_3 at 85% RH. D_0 is the mobility size of monodisperse particles at lowest RH at 20°C. Open and solid symbols correspond to hydration and dehydration curves, respectively.

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